Using Photo-Fenton and Floatation Techniques for the Sustainable Management of Flow-Back Produced Water Reuse in Shale Reservoirs Exploration

Jin, Yi; Davarpanah, Afshin

Published in:
Water, Air, and Soil Pollution

DOI:
10.1007/s11270-020-04812-7

Publication date:
2020

Citation for published version (APA):
Jin, Y., & Davarpanah, A. (2020). Using Photo-Fenton and Floatation Techniques for the Sustainable Management of Flow-Back Produced Water Reuse in Shale Reservoirs Exploration. *Water, Air, and Soil Pollution*, *231*(8), [441]. https://doi.org/10.1007/s11270-020-04812-7

Water Air Soil Pollut (2020) 231:441
https://doi.org/10.1007/s11270-020-04812-7

Check for updates

Using Photo-Fenton and Floatation Techniques for the Sustainable Management of Flow-Back Produced Water Reuse in Shale Reservoirs Exploration

Yi Jin · Afshin Davarpanah

Received: 28 May 2020 / Accepted: 5 August 2020

Abstract Shale reservoirs are one of the unconventional reservoirs that a large volume of hydrocarbon reserves have remained in these reservoirs. Thereby, proper measurement of reservoir characteristics will help to provide an economical and efficient required water as water scarcity has always been a significant challenge throughout recent decades. In this study, eight different production wells in the same formation were selected to consider the required freshwater and reused water for each well as a comparative analysis. According to the results of this study, the percentage of saved water from hydraulic fracturing flow-back water is approximately 85%. Therefore, it only needs 15% of freshwater to continue fracturing process each day, and photo-Fenton and floatation would be an excellent method to remove solids and chemicals from flow-back water. Furthermore, the percentage of saved water from water flooding processes and chemical enhanced oil recovery methods is approximately 70% and 75%, respectively. Therefore, it only needs 30% and 25% of freshwater to continue water flooding processes and chemical enhanced oil recovery methods each day. The approximate total volume of annual saved water is 104 MM m^3 in which 1000 inhabitants could be still alive, and it will not be necessary to use the extreme volume of sweet water for hydrocarbon production.

Keywords Shale reservoirs · Water reuse · Photo-Fenton and floatation method · Annual saved water · Chemical enhanced oil recovery

Y. Jin (✉)
Department of Art Design and Media, East China University of Science and Technology, Shanghai 200237, China
e-mail: 2672479@qq.com

A. Davarpanah (✉)
Department of Mathematics, Aberystwyth University, Aberystwyth, UK
e-mail: afd6@aber.ac.uk

1 Introduction

Water scarcity issues have been considered one of the crucial and challenging concepts in the current decades throughput the world. Therefore, providing sufficient and reasonable water resources for industrial purposes is of importance as freshwater supplementary sources have been reduced (Davarpanah 2018a, b; Davarpanah and Mirshekari 2019a). Shale reservoir regarding their unique property to adsorb large volumes of water would be a huge water consumption during production operations. As a result, the management of treated water in these types of reservoirs would virtually eliminate the necessity of freshwater supply (Davarpanah and Mirshekari 2019b; Davarpanah et al. 2019). Produced water treatment and reuse it in the operational performances have always been a challenge for petroleum industries (Ibrahim et al. 2020; Lusinier et al. 2019; Liden et al. 2019). The produced water included chemical pollutants, heavy and toxic metals, and hydrocarbon droplets (Al-Ghouti et al. 2019; Hansen et al. 2020; de Melo Guedes et al. 2020). Regarding the industrial demand for producing more oil volumes as it is required for numerous related industries, water treatment issues have taken into consideration. Water treatment methods are contained chemical (oxidation, precipitation), biological (biological aerated filters and activated sludge), and physical (adsorption and membrane filtration) that should be technically considered in industrial processes (Al-Ghouti et al. 2019; Jorden and Vermeulen 2019; Vorontsov 2019). Flow-back produced water is not a single-phase as it contains complex components of inorganic and organic materials that are hazardous for the environment (Ali et al. 2019; Gwenzi et al. 2017; Li et al. 2019). The properties of chemical components would vary due to the extraction method, age and depth of the drilled formation, produced hydrocarbons, geographic location, and the geochemistry of the formation. Moreover, the toxicity of these chemical components and heavy metals is ten times higher than the produced oil (Duraisamy et al. 2013). More details about the treatment methods and their mechanisms are explicitly illustrated in Duraisamy et al. (2013).

Roychaudhuri et al. (2019) conducted an investigation considering the significant impact of dissolved salts in the reinjected water. They focused on the separation of divalent anions (SO_4^{2-} and CO_3^{2-}) and cations (Ba^{2+}, Ca^{2+}, and Sr^{2+}) that might interact with the clay fractions and caused to pore blockage. To remove these compositions, membrane filtration or chemical treatment would be efficient. Thereby, they considered the effect of these compositions on clean-up and pretreatment processes with the gas shale reservoir characteristics in Marcellus shale formation (Roychaudhuri et al. 2019). Chang et al. (2019) analyzed the gravity-driven membrane (henceforth; GDM) filtration performances as an effective way to pretreat produced water. They concluded that the gravity-driven membrane filtration method provided more satisfying results rather than other techniques due to the higher permeate fluxes and more organic removals (Chang et al. 2019). Coonrod et al. (2020) provided a comprehensive review that is based on the composition and U-PW quantity analysis of Bakken formation in the USA. They administered geographical survey data to provide a reasonable plan for the improvement of reuse/recycle water in a cost-efficient way. Moreover, they highlighted different treatment processes such as desalination, divalent ion removal, oxidation, and floatation and methods to remove the toxic composition from reinjected water (Coonrod et al. 2020). Photo-Fenton processes are known as the mixture of UV radiation and hydrogen peroxide with Fe^{3+} and Fe^{2+} ion to provide more hydroxyl radicals, which can improve the degradation of the organic pollutants. Ferrous ions photochemical regeneration has occurred by ferric ions photoreduction. Mixture of ferrous ions with hydroxyl radical follows the equations (Ameta et al. 2018; da Silva et al. 2015):

$$Fe3++H2O+hv \rightarrow Fe2++.OH+H+ \tag{1}$$

$$Fe3++H2O+hv \rightarrow Fe2++H2O.+H+ \tag{2}$$

New technologies and treatment methods have given the petroleum industries to minimize the pollution issues and vast expenditures appropriately. Lord et al. (2013) proposed a comprehensive study on purifying the flow-back water by the consideration of fluid compositions (Lord et al. 2013). Zhang et al. (2020) investigated the management of reusing water in hydraulic fracturing processes in shale reservoirs. They focused on the interaction of rock and injected fluid in dynamic and static condition. By the utilization of scanning electron microscope (henceforth SEM), they did some experiments to measure particle sizes, ion contents, zeta potential, and total dissolved solids (henceforth TDS) which can give other scientists and companies good feedback about the produced water in the surface. Therefore, water treatment would be more efficient with knowledge of some information and properties of produced water in shale reservoirs. Moreover, they concluded that injected water composition would play a substantial role in formation damage (Zhang et al. 2020). Shi et al. (2020) investigated the water reused volume estimation in Fuling gas field production in China. They concluded that water volume that is used for fracturing processes for each well is about 34,756.0 m^3 that covered about 98% of total required water. They showed that at the end of 2017, 95% of this water volume is supplied by the flow-back water that provide significant insights for water management plans (Shi et al. 2020). Scanlon et al. (2020) proposed an experimental evaluation on the produced water quantification for different water demanding sectors due to the quality of produced water treatment and its reuse for gas and oil shale layers. They concluded that appropriate treatment of produced water would reduce the necessity of required water for hydraulic fracturing processes (Scanlon et al. 2020).

In this study, eight different production wells in the same formation were selected to consider the required freshwater and reused water for each well as a comparative analysis. Photo-Fenton and flotation method were used in the treatment of produced water. To do this, the required water and treated water for hydraulic fracturing processes, water flooding, and chemical enhanced recovery processes were compared together for each well, and the total water saving is estimated annually.

2 Methodology

2.1 Reservoir Characteristics

To study the required water and how to measure the volume of reusing water in the drilling and production operations, it is vitally essential to have an accurate understanding of the reservoir characteristics, the types of enhanced oil recovery techniques, produced water in each process, the volume of required freshwater, and treatment methods that are used in this field. Shale reservoirs are one of the unconventional reservoirs that a large volume of hydrocarbon reserves have remained in these reservoirs. Thereby, proper measurement of reservoir characteristics will help to provide an economical and efficient required water as water scarcity has always been a significant challenge throughout recent decades. In this study, eight different production wells in the same formation were selected to consider the required freshwater and reused water for each well as a comparative analysis. Porosity is defined as the ratio of pore volume to bulk volume, and it is a dimensionless parameter (which is usually shown as percent or fraction). Permeability is defined as the fluid ability to flow through porous media which depended on the porosity. Porosity and permeability determination is done by different methods, and to be more accurate, petroleum industries use NMR method and X-Ray method which is described in more detail in Davarpanah et al. (2018). Reservoir characteristics for each well are statistically depicted in Table 1. This selection was based on the presence of three phases of oil, water, and gas in each well. In wells A–C, all phases are presented, and as it is expected, water permeability is the highest regarding the particular property of shale reservoirs to absorb water, and therefore the water can be mobilized more. Wells D–F is located in gas shale reservoir, and any water and oil have existed in these wells. As gas can mobilize through the low permeable pores and small pore throats, this property should be considered in comparison with other wells as it does not need any water to produce the remained gas.

2.2 Hydraulic Fracturing

Hydraulic fracturing is one of the influential methods when oil or gas production is drastically decreased, and continuing the production operation is not economical. In this situation, hydraulic fracturing is used to widen the existed pores or create new channels to improve fluid mobilization. Water is one of the essential fluids in this process that combined with chemical additives (about 1% of total water to control the formation damage). Therefore, a large volume of water is required for this process, and this is why the importance of reusing water is highlighted in petroleum industries. However, the environmental aspect of water treatment should be taken into consideration. On the other hand, water quality has played a substantial role in fracturing processes as the water impurities could desirably influence the chemical additives. Thereby, providing high-quality water is prioritized in fracturing processes.

Approximately 15–22 e^{+3} m^3 of water are required for hydraulic fracturing processes; however, shale gas reservoirs are smaller than water shale reservoirs (Lebas et al. 2013). Thereby, the water treatment system is designed in the location that is relatively close to the production wells to virtually eliminate the unnecessary expenses of water transport from considerable distances.

2.3 Separation Units

Produced water entered into the separation system to be more purified. The environmental assessment should be considered in the treatment plan, as formation components that are produced with water are almost hazardous and toxic. Some disposal wells were drilled in the field to transfer toxic materials after separation to reduce environmental pollution (Lord et al. 2013). The main procedure of water treatment in oilfields is schematically described in Fig. 1.

According to Fig. 1, produced water was conducted to primary separation and secondary separation. In primary separation, as it is depicted in Fig. 2, it is concentrated on the removal of the suspended hydrocarbons and existed solids from the produced water. In the first step, three phases of oil, gas, and water are separated

Table 1 Reservoir characteristics for each well

Well	Porosity (%)	Water permeability (mD)	Oil permeability (mD)	Gas permeability (mD)
Well A	2.14	17.2	12.45	0.9
Well B	5.26	18.0	10.63	1.32
Well C	6.54	16.94	9.32	0.74
Well D	2.87	–	–	2.85
Well E	7.63	–	–	3.15
Well F	3.28	–	–	2.67
Well G	3.51	20.74	8.45	–
Well H	4.37	24.75	7.38	–

regarding their densities. Separated water was conducted to the dissolved gas flotation (henceforth DGF) by addition of chemical agents to separate suspended solids, oil, and other macromolecules. Finally, it had transferred to sand filters to separate micromolecules and sands before entering to secondary separation section.

Secondary separation has contained physical, biological, chemical, and membrane treatment for water treatment. In this field, the photo-Fenton and floatation method is used to eliminate the aromatics and small oil droplets in the flotation process for 10 min. The efficiency of this technique is about 99% .

3 Results and Discussion

3.1 Hydraulic Fracturing Process

In this part of the study, we predict the average required water for hydraulic fracturing processes for each operational day and then compare it with flow-back water measurement after treatment processes to calculate the efficiency of photo-Fenton and floatation method and how much water will be additionally required. The required water and treated water after separation processes are schematically depicted in Fig. 3. As can be seen in Fig. 3, well G and well H that included more

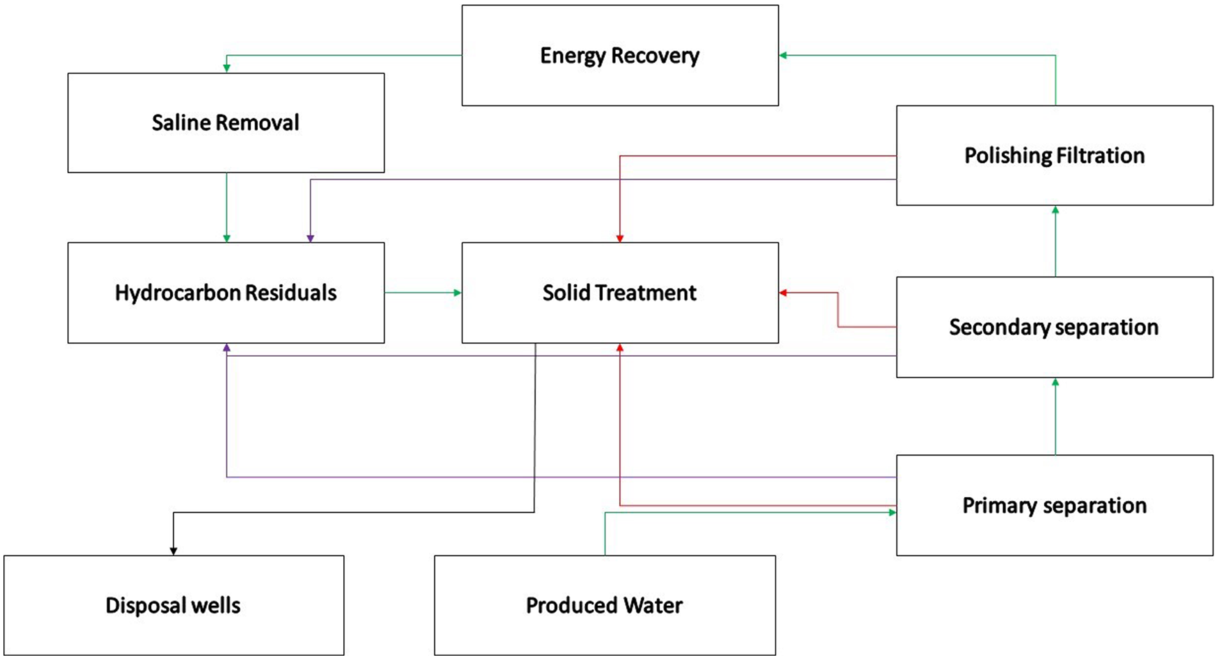

Fig. 1 The main procedure of water treatment in oilfields

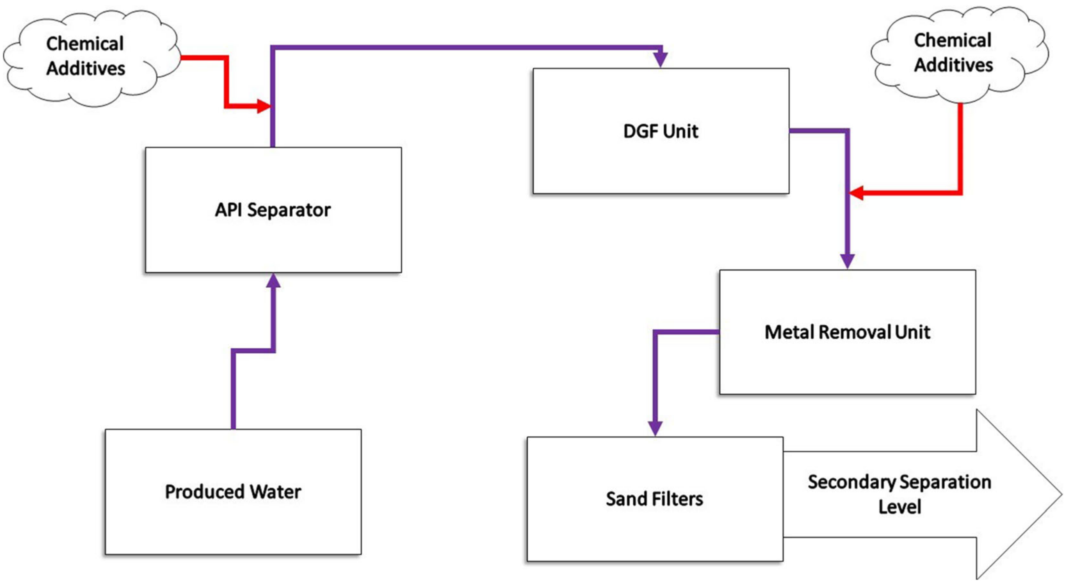

Fig. 2 Primary treatment procedure

water volume will require a lower volume for fracturing performances.

The total of saved water is calculated from Eq. (3).

$$\text{Percentage of Saved Water} = \frac{Required\ Water - Treated\ Water}{Required\ Water} *100 \quad (3)$$

According to Eq. (3), percentage of saved water from hydraulic fracturing flow-back water is approximately 85%. Therefore, it only needs 15% of freshwater to continue fracturing process each day, and photo-Fenton and floatation would be an excellent method to remove solids and chemicals from flow-back water. Shi et al. (2020) investigated the water reused volume estimation in Fuling gas field production in China. They concluded that water volume that is used for fracturing processes for each well is about 34,756.0 m^3 that covered about 98% of total required water. They showed that at the

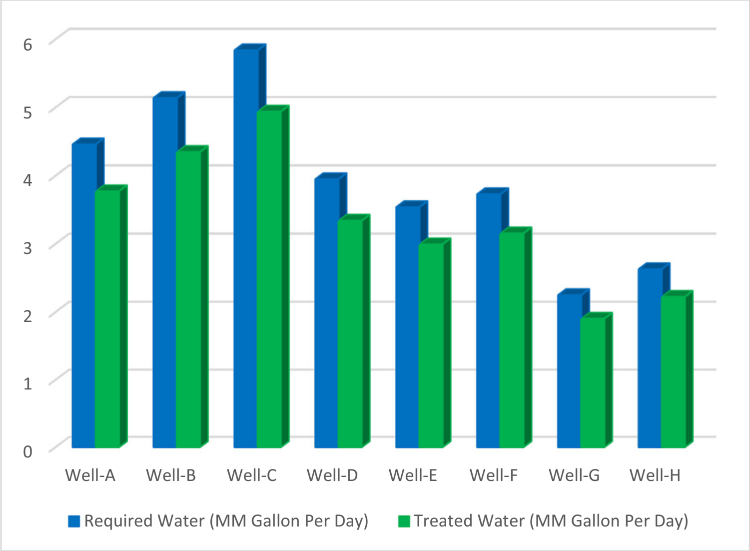

Fig. 3 Required and treated water for hydraulic fracturing processes

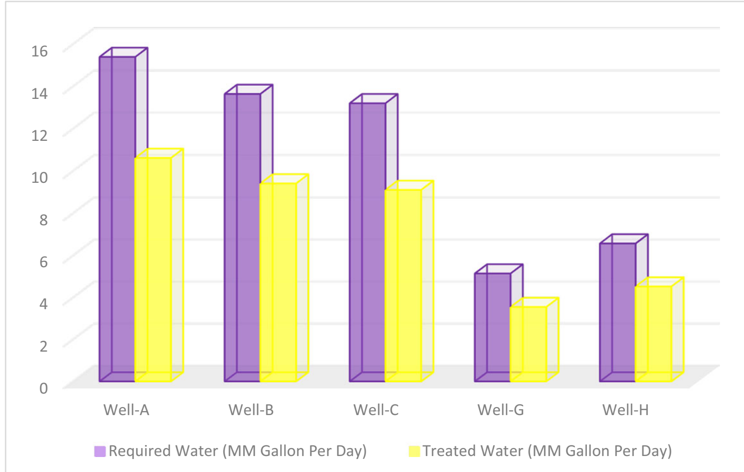

Fig. 4 Required and treated water for water flooding processes

end of 2017, 95% of this water volume is supplied by the flow-back water that provide significant insights for water management plans (Shi et al. 2020).

3.2 Enhanced Oil Recovery Methods

As most of the enhanced oil recovery methods, especially chemical flooding, will need water to operate as a solvent and enhance oil recovery, required water should be provided to continue the flooding performances. Chemical flooding methods that required water in their processes are surfactant flooding and foam flooding that are suitable for shale reservoirs. Water flooding is one of the primary methods that need a large volume of water. Thereby, as can be seen in Figs. 4 and 5, the required water and treated water for each well are schematically plotted to calculate the saved water per day. In wells D–F, as water-related techniques are not economical and efficient, there are no any water-related techniques to enhance recovery factor.

According to Eq. (3), percentage of saved water from water flooding processes and chemical enhanced oil recovery methods is approximately 70% and 75%, respectively. Therefore, it only needs 30% and 25% of freshwater to continue water flooding processes and chemical enhanced oil recovery methods each day, and photo-Fenton and floatation would be an excellent method to remove solids and chemicals from flow-back water.

Annual saved water is schematically plotted in Fig. 6, which indicated large volume of water for each well. The approximate total volume of annual saved water is 104 MM m^3 in which 1000 inhabitants could be still alive, and it will not be necessary to use the extreme volume of sweet water for hydrocarbon production.

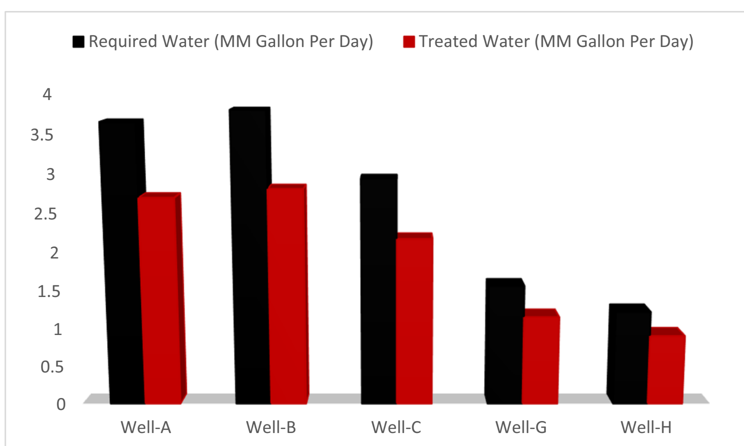

Fig. 5 Required and treated water for chemical enhanced oil recovery methods

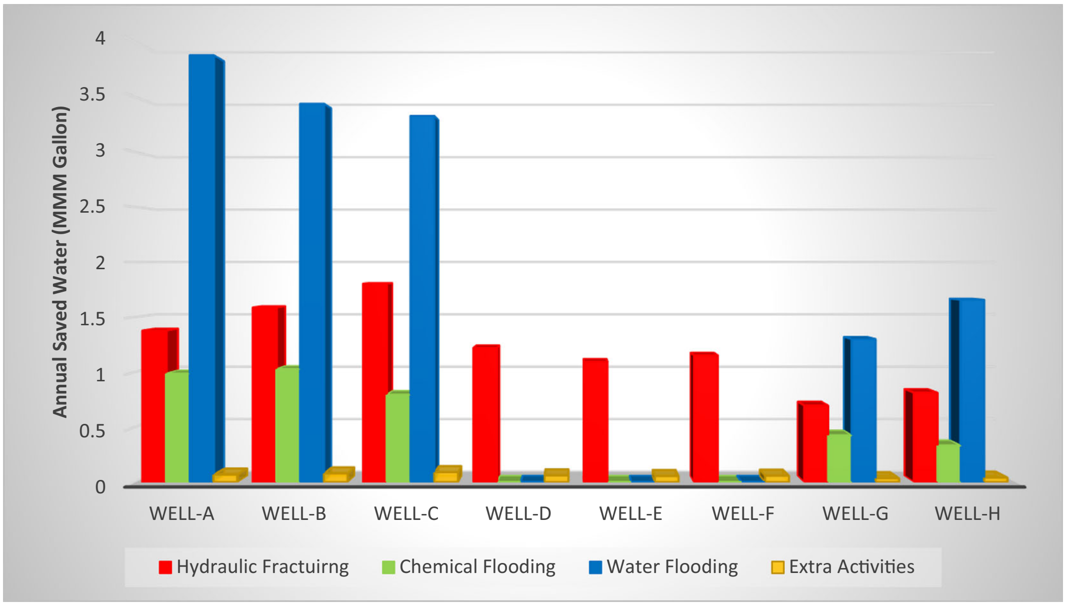

Fig. 6 Annual saved water for each well in different water utilization

4 Conclusion

Water treatment management is considered to be one of the significant issues in shale reservoirs as it needs large volumes of freshwater supply for production operations. Moreover, as produced water has different hazardous materials that would have a negative impact on the environment, it is necessary to treat produced water precisely in each step. The main conclusions of this study are as follows:

- Percentage of saved water from water flooding processes and chemical enhanced oil recovery methods is approximately 70% and 75%, respectively. Therefore, it only needs 30% and 25% of freshwater to continue water flooding processes and chemical enhanced oil recovery methods each day.
- Percentage of saved water from hydraulic fracturing flow-back water is approximately 85%. Therefore, it only needs 15% of freshwater to continue fracturing process each day.
- Photo-Fenton and floatation would be an excellent method to remove solids and chemicals from flow-back water.
- The approximate total volume of annual saved water is 104 MM m^3 in which 1000 inhabitants could be still alive, and it will not be necessary to use the extreme volume of sweet water for hydrocarbon production.

Acknowledgements We would like to acknowledge the following:

1. Exploring Funding of East China University of Science and Technology (No. JKZ012022002)
2. Youth Program of National Natural Science Foundation of China (No. 51668066)
3. Shanghai Summit Discipline Open Funding (No. DA18301).

Data Availability All data, models, and code generated or used during the study appear in the submitted article.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

Al-Ghouti, M. A., Al-Kaabi, M. A., Ashfaq, M. Y., & Da'na, D. A. (2019). Produced water characteristics, treatment and reuse: A review. *Journal of Water Process Engineering, 28*, 222–239.

Ali, S., Rehman, S. A. U., Luan, H.-Y., Farid, M. U., & Huang, H. (2019). Challenges and opportunities in functional carbon nanotubes for membrane-based water treatment and desalination. *Science of the Total Environment, 646*, 1126–1139.

Ameta, R. K., Chohadia, A., Jain, A., & Punjabi, P. B. (2018). Chapter 3 - Fenton and photo-Fenton processes. In S. C.

Ameta & R. Ameta (Eds.), *Advanced oxidation processes for waste water treatment* (pp. 49–87). Academic Press.

Chang, H., Liu, B., Wang, H., Zhang, S.-Y., Chen, S., Tiraferri, A., et al. (2019). Evaluating the performance of gravity-driven membrane filtration as desalination pretreatment of shale gas flowback and produced water. *Journal of Membrane Science, 587*, 117187.

Coonrod, C. L., Yin, Y. B., Hanna, T., Atkinson, A., Alvarez, P. J., Tekavec, T. N., et al. (2020). *Fit-for-purpose treatment goals for produced waters in shale oil and gas fields* (p. 115467). *Water Research*.

da Silva, S. S., Chiavone-Filho, O., de Barros Neto, E. L., & Foletto, E. L. (2015). Oil removal from produced water by conjugation of flotation and photo-Fenton processes. *Journal of Environmental Management, 147*, 257–263.

Davarpanah, A. (2018a). A feasible visual investigation for associative foam >\ polymer injectivity performances in the oil recovery enhancement. *European Polymer Journal, 105*, 405–411. https://doi.org/10.1016/j.eurpolymj.2018.06.017.

Davarpanah, A. (2018b). The feasible visual laboratory investigation of formate fluids on the rheological properties of a shale formation. [journal article]. *International Journal of Environmental Science and Technology*. https://doi.org/10.1007/s13762-018-1877-6.

Davarpanah, A., & Mirshekari, B. (2019a). Experimental investigation and mathematical modeling of gas diffusivity by carbon dioxide and methane kinetic adsorption. *Industrial & Engineering Chemistry Research*. https://doi.org/10.1021/acs.iecr.9b01920.

Davarpanah, A., & Mirshekari, B. (2019b). Mathematical modeling of injectivity damage with oil droplets in the waste produced water re-injection of the linear flow. *Eur. Phys. J. Plus, 134*(4), 180.

Davarpanah, A., Mirshekari, B., Jafari Behbahani, T., & Hemmati, M. (2018). Integrated production logging tools approach for convenient experimental individual layer permeability measurements in a multi-layered fractured reservoir. [journal article]. *Journal of Petroleum Exploration and Production Technology, 8*(3), 743–751. https://doi.org/10.1007/s13202-017-0422-3.

Davarpanah, A., Mirshekari, B., & Razmjoo, A. A. (2019). A simulation study of water injection and gas injectivity scenarios in a fractured carbonate reservoir: A comparative study. *Petroleum Research*. https://doi.org/10.1016/j.ptlrs.2019.02.001.

de Melo Guedes, L. F., Braz, B. F., Freire, A. S., & Santelli, R. E. (2020). Assessing the harmfulness of high-salinity oilfield-produced water related to trace metals using vortex-assisted dispersive liquid-liquid microextraction combined with inductively coupled plasma optical emission spectrometry. *Microchemical Journal, 155*, 104714.

Duraisamy, R. T., Beni, A. H., & Henni, A. (2013). *State of the art treatment of produced water* (pp. 199–222). *Water Treatment*.

Gwenzi, W., Chaukura, N., Noubactep, C., & Mukome, F. N. (2017). Biochar-based water treatment systems as a potential low-cost and sustainable technology for clean water provision. *Journal of Environmental Management, 197*, 732–749.

Hansen, B. H., Sørensen, L., Størseth, T. R., Altin, D., Gonzalez, S. V., Skancke, J., et al. (2020). The use of PAH, metabolite and lipid profiling to assess exposure and effects of produced water discharges on pelagic copepods. *Science of the Total Environment, 714*, 136674.

Ibrahim, M. H., Moussa, D. T., El-Naas, M. H., & Nasser, M. S. (2020). A perforated electrode design for passivation reduction during the electrochemical treatment of produced water. *Journal of Water Process Engineering, 33*, 101091.

Jorden, R. M., & Vermeulen, B. (2019). Methods and systems for optimizing water treatment coagulant dosing. Google Patents.

Lebas, R. A., Shahan, T. W., Lord, P., & Luna, D. (2013) Development and use of high-TDS recycled produced water for crosslinked-gel-based hydraulic fracturing. In *SPE Hydraulic Fracturing Technology Conference*: Society of Petroleum Engineers.

Li, J., Dou, X., Qin, H., Sun, Y., Yin, D., & Guan, X. (2019). Characterization methods of zerovalent iron for water treatment and remediation. *Water Research, 148*, 70–85.

Liden, T., Carlton Jr., D. D., Miyazaki, S., Otoyo, T., & Schug, K. A. (2019). Comparison of the degree of fouling at various flux rates and modes of operation using forward osmosis for remediation of produced water from unconventional oil and gas development. *Science of the Total Environment, 675*, 73–80.

Lord, P., Weston, M., Fontenelle, L. K., & Haggstrom, J. (2013). *Recycling water: Case studies in designing fracturing fluids using flowback, produced, and nontraditional water sources*. Lima: Paper presented at the SPE Latin-American and Caribbean Health, Safety, Environment and Social Responsibility Conference.

Lusinier, N., Seyssiecq, I., Sambusiti, C., Jacob, M., Lesage, N., & Roche, N. (2019). Biological treatments of oilfield produced water: A comprehensive review. *SPE Journal.*

Paluszny, A., Salimzadeh, S., & Zimmerman, R. W. (2018). Chapter 1 - Finite-element modeling of the growth and interaction of hydraulic fractures in poroelastic rock formations. In Y.-S. Wu (Ed.), *Hydraulic Fracture Modeling* (pp. 1–19). Gulf professional publishing.

Roychaudhuri, B., Tsotsis, T., & Jessen, K. (2019). Shale-fluid interactions during forced lmbibition and flow-back. *Journal of Petroleum Science and Engineering, 172*, 443–453.

Scanlon, B. R., Reedy, R. C., Xu, P., Engle, M., Nicot, J. P., Yoxtheimer, D., et al. (2020). Can we beneficially reuse produced water from oil and gas extraction in the U.S.? *Science of The Total Environment, 717*, 137085. https://doi.org/10.1016/j.scitotenv.2020.137085.

Shi, W., Wang, X., Guo, M., Shi, Y., Feng, A., Liang, R., et al. (2020). Water use for shale gas development in China's Fuling shale gas field. *Journal of Cleaner Production, 256*, 120680. https://doi.org/10.1016/j.jclepro.2020.120680.

Vorontsov, A. V. (2019). Advancing Fenton and photo-Fenton water treatment through the catalyst design. *Journal of Hazardous Materials, 372*, 103–112.

Zhang, L., Tice, M., & Hascakir, B. (2020). A laboratory study of the impact of reinjecting flowback fluids on formation damage in the Marcellus shale. *SPE Journal.*